Fundamental Physics with Gravitational Waves

When GWs will finally be detected,
the realm of physics, the territory subject to our
observations, analysis, investigations, will suddenly expand:
we will be able to study strongly gravitating systems and processes,
of which - up to now - we only have indirect evidence or knowledge.

Many fundamental questions are without answer, until we start
exploring the uncharted territory of strong gravity.

Some of them are related to the nature and the behaviour
of fundamental interactions, like gravity itself,
or - for instance - nuclear physics.
Others are related to the nature and the evolution
of the objects populating our Universe, and, ultimately,
of the Universe itself.

I will briefly discuss some of the fundamental questions
which we will be able to address
when GW will open a new window on the universe.

1) GW are perfect probes of gravity and matter in *extreme* conditions

- Which is the nature of the gravitational interaction in the strong-field regime?

  We have centuries of observations and experiments of gravity in weak-field, but no direct data on the strong-field regime,

  as for instance near a black hole horizon, or inside a neutron star.

  - Is gravity described by General Relativity in this regime?
  - How general are the "no-hair theorems" of black holes?

- Which is the behaviour of matter at supra-nuclear densities?

  The behaviour of matter at supra-nuclear densities typical of a neutron star inner core is largely unknown: such extreme conditions can not be reproduced in a laboratory, and are a challenge for the theory. Even the particle content (hyperons? deconfined quarks? Bose condensates?) is unknown.

- Do new *fundamental fields* couple with strong-gravity systems?

  ultra-light (axion-like?) fields, possible DM candidates?

2) *GW astronomy* will open a new observational window on the Universe providing unique information on the emitting sources:

- How do black holes of different mass scales form and evolve?
- Does compact object coalescence source gamma-ray bursts?
- Which is the trigger of supernovae explosion?
- Why neutron stars do not spin faster?
- Can we learn more on the origin and evolution of our Universe using gravitational waves?
- Will *totally unexpected sources* show up?

Some of these questions will also be addressed in the context of *multimessenger astronomy* (see Punturo's talk)